

A&A 370, 170–175 (2001)
 DOI: 10.1051/0004-6361:20010192
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**Astronomy
&
Astrophysics**

The origin of the runaway high-mass X-ray binary HD 153919/4U1700-37[★]

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Received 8 September 2000 / Accepted 31 January 2001

Abstract. Based on its *Hipparcos* proper motion, we propose that the high-mass X-ray binary HD 153919/4U1700-37 originates in the OB association Sco OB1. At a distance of 1.9 kpc the space velocity of 4U1700-37 with respect to Sco OB1 is 75 km s⁻¹. This runaway velocity indicates that the progenitor of the compact X-ray source lost about 7 M_{\odot} during the (assumed symmetric) supernova explosion. The system’s kinematical age is about 2 ± 0.5 million years which marks the date of the supernova explosion forming the compact object. The present age of Sco OB1 is $\lesssim 8$ Myr; its suggested core, NGC 6231, seems to be somewhat younger (~ 5 Myr). If HD 153919/4U1700-37 was born as a member of Sco OB1, this implies that the initially most massive star in the system terminated its evolution within $\lesssim 6$ million years, corresponding to an initial mass $\gtrsim 30 M_{\odot}$. With these parameters the evolution of the binary system can be constrained.

Key words. stars: early type – stars: mass loss – stars: neutron – stars: individual: HD 153919 – 4U1700-37 – ultraviolet: stars

1. Introduction

The massive stars in the Milky Way are not randomly distributed, but are concentrated in loose groups called OB associations located in the spiral arms of our galaxy (for a review, see e.g. Brown et al. 1999). About 80% of the O stars are member of an OB association; the kinematical properties of the remaining 20% of the field population suggest that these O stars are runaways, i.e. they were born in an OB association, but at a certain stage they escaped from it (Blaauw 1993). The two most popular scenarios to explain the existence of runaway stars are (i) the dynamical ejection from a young cluster (Poveda et al. 1967) and (ii) the supernova of the companion star in a massive binary (Blaauw 1961). A recent study by Hoogerwerf et al. (2000) based on *Hipparcos* data demonstrates that both scenarios are at work, probably at a rate of 1:2, respectively.

High-mass X-ray binaries (HMXBs) are the descendants of massive binaries (Van den Heuvel & Heise 1972).

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[★] Based on data obtained with ESA’s astrometric satellite *Hipparcos*.

A neutron star or a black hole, the compact remnant of the initially most massive star (the primary) in the binary system, produces X-rays due to the accretion of matter from the secondary (an OB supergiant or a Be star); see Kaper (1998) for an overview of the OB-supergiant systems. The binary system remains bound after the supernova, if less than 50% of the total system mass is lost during the (assumed symmetric) explosion (Blaauw 1961; Boersma 1961). The latter can be understood if one considers the phase of mass transfer occurring when the primary becomes larger than its critical Roche lobe (e.g. at the end of core-hydrogen burning when the star expands to become a supergiant) and matter flows from the primary to the secondary. This results in a change of the mass ratio from larger to smaller than one. A kick exerted on the compact object due to the eventual asymmetry of the supernova explosion has also to be taken into account when determining whether the binary breaks up or remains bound after the supernova.

According to the binary-supernova scenario all HMXBs should be runaways. Gies & Bolton (1986) did not find observational evidence supporting this hypothesis on the basis of radial-velocity measurements, though Van Oijen (1989) found strong indications that HMXBs

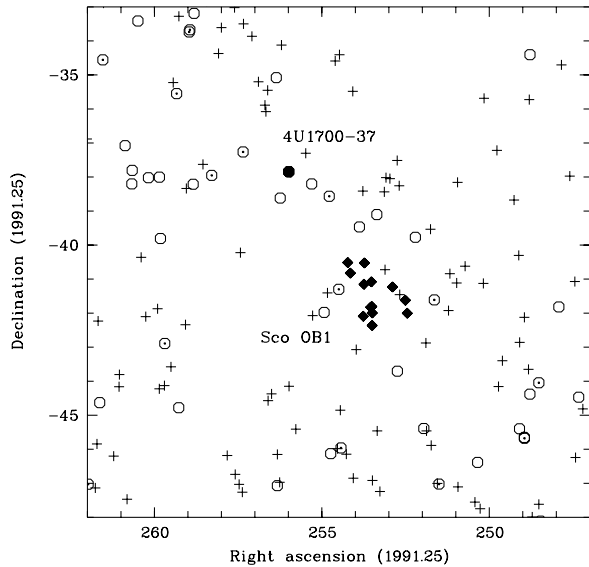


Fig. 1. O- and B-type stars selected from the *Hipparcos* catalogue in the field of HD 153919/4U1700-37 (filled circle). The confirmed members of Sco OB1 are shown as filled diamonds. The plus symbols correspond to OB stars with a parallax larger than 1 mas (i.e. distance smaller than 1 kpc) and were eliminated from the membership analysis. The open circles indicate stars with a (photometric) distance within the range of Sco OB1; some of them, with a proper motion similar to the confirmed association members, are indicated by a circle with central dot (cf. Fig. 2). The latter close to Sco OB1 might be members as well

are high-velocity objects. Based on pre-*Hipparcos* proper motion measurements, Van Rensbergen et al. (1996) suggested that the HMXB Vela X-1 is a runaway system produced by the supernova scenario, and that it originates in the OB association Vel OB1. The discovery of a wind-bow shock around Vela X-1 showed that this system indeed is running through interstellar space with a supersonic velocity, proving the runaway nature of this HMXB (Kaper et al. 1997). The *Hipparcos* proper motions of a dozen HMXBs (Chevalier & Ilovaisky 1998; Kaper et al. 1999) finally demonstrated that, as expected, likely all HMXBs are runaways. The most massive systems (those hosting an OB supergiant) have a mean peculiar (i.e. with respect to their standard of rest) tangential velocity of about 40 km s^{-1} , whereas the Be/X-ray binaries have on average lower velocities (about 15 km s^{-1}). This difference in velocity is consistent with the predictions of binary evolution (Van den Heuvel et al. 2000).

The identification of the “parent” OB association of a HMXB is important, because it provides unique constraints on the evolution of high-mass X-ray binaries. When the system’s proper motion and parent OB association are known, its kinematical age can be derived. The kinematical age marks the time of the supernova that produced the compact X-ray source. The distance of a HMXB usually is quite uncertain (and required to calculate its space velocity), but the distance to an OB association can be determined with better accuracy. The space velocity

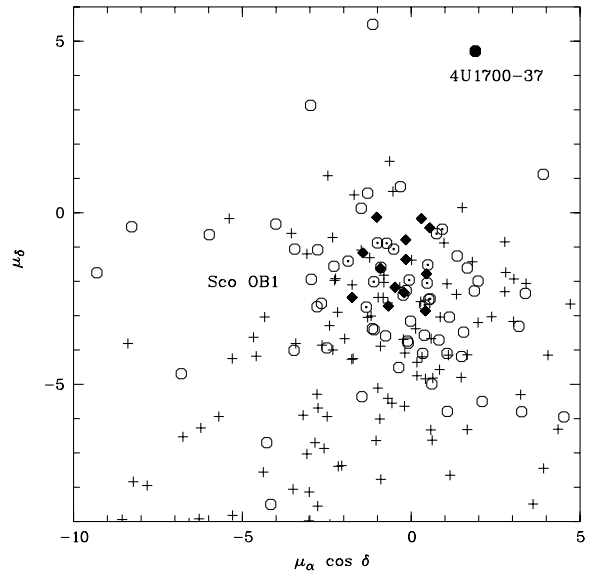


Fig. 2. The *Hipparcos* proper motions of the OB stars shown in Fig. 1. The filled diamonds represent the confirmed members of Sco OB1; these stars cluster both in location and in proper motion. The plusses and open circles indicate the OB stars we could, or could not exclude on the basis of a distance estimate, respectively. The circles with a central dot are stars with similar proper motion and photometric distance as the confirmed cluster members. Also shown is 4U1700-37 (filled circle) which obviously has a proper motion different from that of Sco OB1

relates to the amount of mass lost from the system during the supernova explosion (cf. Nelemans et al. 1999). The age of the parent OB association should be equal to the age of the binary system. Consequently, the turn-off mass at the time of supernova yields the initial mass of the primary. Thus, this relatively straightforward observation can be used to determine the age of the system, the time of supernova of the primary, the initial mass of the primary, and the amount of mass lost from the system during the supernova. Combining this information allows one to put constraints on the initial orbital parameters of the progenitor of the HMXB and on the evolutionary history of the system.

Here we apply this to the system HD 153919/4U1700-37. HD 153919 ($m_V = 6.6$) is the O6.5 Iaf+ companion to 4U1700-37, most likely a neutron star powered by wind accretion (Jones et al. 1973; Haberl et al. 1989), although no X-ray pulsations have been detected (Gottwald et al. 1986). According to Brown et al. (1996) 4U1700-37 is a good candidate for a low-mass black hole. HD 153919 is the hottest OB companion star known in a HMXB; therefore, the progenitor of 4U1700-37 potentially is a very massive star. Chevalier & Ilovaisky (1998) showed that the *Hipparcos* proper motion of HD 153919 (5 mas yr^{-1}) corresponds to a peculiar tangential motion of 57 km s^{-1} for an adopted distance of 1.7 kpc (Bolton & Herbst 1976), which proves the runaway nature of the system.

In the following we will use the *Hipparcos* data of OB-type stars in the Sco-Cen region to search for the parent

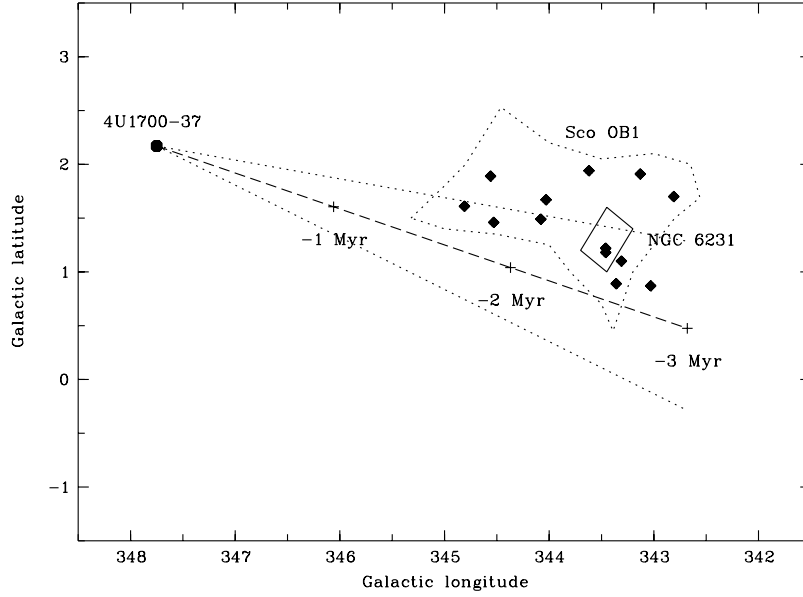


Fig. 3. The reconstructed path of the runaway HMXB 4U1700-37 intersects with the location of Sco OB1; the error cone is indicated by the dotted straight lines. The *Hipparcos* confirmed members are shown as filled diamonds. The dotted line marks the region studied by Perry et al. (1991), including the young open cluster NGC 6231 (box). The proper motion of 4U1700-37 is with respect to the average proper motion of Sco OB1. The corresponding kinematical age of 4U1700-37 is 2 ± 0.5 million year. The current angular separation between 4U1700-37 and NGC 6231 (at 2 kpc) corresponds to a distance of about 150 pc

OB association of 4U1700-37. The result will be used to reconstruct the evolutionary history of the system.

2. Sco OB1: The parent OB association of 4U1700-37

2.1. Early suggestions

We now consider in which association 4U1700-37 may have originated. In their paper on the open cluster NGC 6281, Feinstein & Forte (1974) remark that HD 153919, a comparison star in their study, fits remarkably well the color-magnitude and color-color relations of the open cluster NGC 6231. This cluster, the suggested core of the Sco OB1 association, is a few degrees away from NGC 6281. Feinstein & Forte suggested that HD 153919 may be a runaway star from NGC 6231. Based on the proper motion listed in the Smithsonian Astrophysical Observatory catalogue (13 mas yr^{-1}) they obtained a kinematical age of $1.2 \cdot 10^6 \text{ yr}$, “roughly in agreement with the age of NGC 6231 which is a very young cluster”.

2.2. *Hipparcos* observations of the OB stars around 4U1700-37

In our search for the parent OB association of 4U1700-37 we used the *Hipparcos* database (ESA 1997, Perryman et al. 1997) and selected the OB stars contained in a region of 20×20 degrees centered on 4U1700-37 (Fig. 1). In principle, the *Hipparcos* data (location, magnitude, parallax, and proper motion) of the OB stars should be sufficient to identify the OB associations in that area. However, the *Hipparcos* data, in particular the parallax, are only

accurate enough for OB stars closer than about 1 kpc (cf. De Zeeuw et al. 1999 for a *Hipparcos* census of the nearby OB associations). The estimated distance of 4U1700-37 (1.7 kpc) indicates that the candidate parent OB association of this runaway system is not within the required range for an accurate *Hipparcos* cluster membership analysis. In order to identify the likely members of an OB association we have to rely mainly on the position and proper motion of the O and B-type stars.

The membership list of Humphreys (1978), based on radial-velocity studies, is used as a first indication to locate the OB associations in the area. It turns out that there is only one good candidate parent OB association in the backward direction of 4U1700-37: Sco OB1, for which distances are quoted in the range 1.6–2.3 kpc (Perry et al. 1991; Sung et al. 1998). To eliminate some foreground stars we used the *Hipparcos* parallax. We also calculated photometric distances (taking into account an estimate of the interstellar extinction using the spectral type) to eliminate stars from the *Hipparcos* input list which are either nearby ($d < 1 \text{ kpc}$) or far away ($d > 3 \text{ kpc}$) compared to the distance of Sco OB1.

We identified several members of Sco OB1 in the *Hipparcos* catalogue which are also given as members in Humphreys (1978) and Perry et al. (1991). In Fig. 2 we show the observed proper motions of the OB stars in the field. Using the mean location and mean proper motion of the OB stars in common with those listed in Humphreys and Perry et al., we could identify a few more candidate OB-type members of Sco OB1. The “*Hipparcos* confirmed” members of Sco OB1, with spectral type, proper motion, and radial velocity (from Humphreys 1978 and

Table 1. The confirmed *Hipparcos* members of Sco OB1 and the high-mass X-ray binary HD 153919/4U1700-37. The columns list the HD number, *Hipparcos* catalogue number HIP, the observed proper motion in right ascension and declination, the spectral type (Perry et al. 1991), *V* magnitude, and observed heliocentric radial velocity (from Humphreys 1978), respectively

Members of Sco OB1 (<i>Hipparcos</i> data)						
HD number	HIP	$\mu_\alpha \cos \delta$ (error) (mas yr ⁻¹)	μ_δ (error) (mas yr ⁻¹)	Spectral Type	<i>V</i> (mag)	v_{rad} (km s ⁻¹)
151515	82366	-1.43(0.68)	-1.17(0.56)	O7 II(f)	7.16	var.
151564	82378	-0.91(0.95)	-1.62(0.68)	B0.5 V	7.99	-39.6
152235	82669	-0.21(0.76)	-2.33(0.58)	B0.7 Ia	6.28	-36.0
152234	82676	-1.75(1.44)	-2.47(1.02)	B0.5 Ia	5.46	-6.0
152246	82685	-0.16(0.92)	-0.79(0.62)	O9 III-IVn	7.32	8.0 var.
152405	82767	-1.02(0.88)	-0.13(0.71)	O9.7 Ib-II	7.20	-8
152424	82783	-0.68(0.75)	-2.72(0.57)	OC9.7 Ia	6.30	-18.0 var.
152667	82911	0.30(0.78)	-0.17(0.65)	B0.5 Ia	6.18	-5.0
151804	82493	0.55(0.73)	-0.44(0.54)	O8 Iaf	5.23	-61.0
152236	82671	-0.48(0.75)	-2.17(0.61)	B1.5 Ia+p	4.70	-23.9
152248	82691	0.42(1.46)	-2.86(0.96)	O7 Ib:(f) + O6.5:f	6.07	-44
152408	82775	-0.16(0.67)	-1.36(0.51)	O8: Iafpe	5.78	var.
152723	82936	0.45(1.47)	-1.78(1.04)	O6.5 III(f)	7.10	-3.5
HD 153919/4U1700-37						
153919	83499	1.90(0.78)	4.71(0.48)	O6.5Iaf+	6.48	-60.0

Gies & Bolton 1986) are listed in Table 1 and are indicated in the figures with a filled diamond. The mean proper motion of these members, and thus an estimate of the proper motion of Sco OB1, is: $\mu_\alpha \cos \delta = -0.39$ mas yr⁻¹, $\mu_\delta = -1.54$ mas yr⁻¹. This is in close agreement with the proper motion expected on the basis of differential galactic rotation and peculiar solar motion; correction for the latter two effects gives $\mu_1^{\text{pec}} = 0.57$ mas yr⁻¹ and $\mu_b^{\text{pec}} = -0.10$ mas yr⁻¹, which corresponds to a tangential velocity of ~ 5 km s⁻¹ with respect to its standard of rest.

2.3. The kinematical age of 4U1700-37

Figure 3 displays the *Hipparcos* members of Sco OB1. We have also indicated the area of Sco OB1 studied by Perry et al. (1991; note that the association might well extend beyond these borders) as well as the location of the open cluster NGC 6231, the suggested nucleus of Sco OB1. Subtraction of the average proper motion of Sco OB1 from the observed proper motion of HD 153919 (4U1700-37) results in the path sketched in Fig. 3. In principle, the galactic potential should be taken into account when reconstructing the path of the runaway system, but for this relatively short track the corrections will be very small. The uncertainty in the proper motion measurement of HD 153919 (Table 1) allows for a range in position represented by the straight dotted lines. Clearly, 4U1700-37 has been within the area of Sco OB1 about 2 million years ago; also NGC 6231 is included in the error cone. We derive a kinematical age of the system of 2 ± 0.5 million years. Given the large proper motion of the system, the kinematical age can be derived with relatively high precision. Note that this age determination is independent of the adopted distance to 4U1700-37 and Sco OB1.

2.4. The distance and age of Sco OB1

Perry et al. (1991) determine the distance of Sco OB1 at 2.0 kpc, very similar to the 1.9 kpc reported by Humphreys (1978). At a distance of 2 kpc the relative proper motion of 4U1700-37 with respect to Sco OB1 corresponds to a tangential velocity of 58 km s⁻¹. Taking into account the radial velocities of the members of Sco OB1 (mean velocity -14 km s⁻¹, though the radial velocities display a large spread, Humphreys 1978) and of HD 153919 (-60 km s⁻¹, Gies & Bolton 1986), this results in a space velocity of 75 km s⁻¹. As HD 153919 is moving towards us, its present distance is about 100 pc less than Sco OB1, i.e. 1.9 kpc, in agreement with its photometric distance. For NGC 6231, the open cluster inside Sco OB1 (Fig. 3), Balona & Laney (1995) derive a distance modulus of 11.08 ± 0.05 mag, and Sung et al. (1998) arrive at a very similar result: 11.0 ± 0.07 mag, corresponding to a distance of 1.6 kpc. If this is the appropriate distance of the parent association, the present distance of HD 153919 is about 1.5 kpc, and its space velocity with respect to NGC 6231 67 km s⁻¹. Obviously, NGC 6231 might also be an open cluster in front of Sco OB1.

The mean radial velocity of Sco OB1 of -14 km s⁻¹ corresponds to a distance of 2.0 kpc. Neutral hydrogen measurements in the direction of HD 153919 by Benaglia & Cappa (1999) indicate a distance of 2 kpc as well. For the remainder of this paper we adopt a distance of 2 kpc for Sco OB1.

Based on the evolutionary grids of Maeder & Meynet (1988), Perry et al. (1991) derive a logarithmic age of 6.9 ± 0.2 (8 Myr) for Sco OB1 and the open clusters NGC 6231 and Tr 24. For NGC 6231 Balona & Laney (1995) estimate an age of 5 ± 1 Myr. Using the models of Schaller et al. (1992), Sung et al. (1998) derive an age of 2.5–4 Myr for the massive stars in NGC 6231. The low-mass stars in this

cluster show a large age spread. NGC 6231 may represent a relatively young region in Sco OB1. Perry et al. (1991) do not find a significant age difference between Sco OB1 and the enclosed clusters NGC 6231 and Tr 24. Anyway, Sco OB1 certainly is a young OB association given the large number of O stars still present.

3. On the evolutionary history of HD 153919/4U1700-37

Our analysis shows that HD 153919/4U1700-37 originates in the OB association Sco OB1, from which it escaped about 2 Myr ago due to the supernova of 4U1700-37's progenitor. At the time of the (assumed symmetric) supernova explosion less than half of the total system mass was lost from the system, as the system remained bound. The amount of mass lost during the supernova explosion (ΔM) can be estimated from the current space velocity v_{sys} of the system. For a circular pre-supernova orbit and a symmetric supernova explosion, Nelemans et al. (1999) derive the following relation between ΔM and v_{sys} :

$$\left(\frac{\Delta M}{M_{\odot}}\right) = \left(\frac{v_{\text{sys}}}{213 \text{ km s}^{-1}}\right) \left(\frac{M}{M_{\odot}}\right)^{-1} \left(\frac{P_{\text{cir}}}{\text{day}}\right)^{\frac{1}{3}} \left(\frac{M+m}{M_{\odot}}\right)^{\frac{5}{3}},$$

where M is the present mass of HD 153919, m the mass of 4U1700-37, and P_{cir} the orbital period after re-circularization of the orbit due to tidal dissipation. The current orbital period of the system is 3.41 day and there is no indication that the orbit is non-circular. As the X-ray source is not pulsating, only the radial-velocity orbit of the O supergiant can be measured, so that the masses of both stars are not uniquely determined. Heap & Corcoran (1992) propose $M = 52 \pm 2 M_{\odot}$ (i.e. a mass corresponding to its spectral type) and $m = 1.8 \pm 0.4 M_{\odot}$; Rubin et al. (1996) argue that $M = 30^{+11}_{-7} M_{\odot}$ and $m = 2.6^{+2.3}_{-1.4} M_{\odot}$. For a space velocity of 75 km s^{-1} , ΔM becomes $8 M_{\odot}$ or $6 M_{\odot}$ for the solution of Heap & Corcoran and Rubin et al., respectively. Therefore, the mass of the star that exploded was about $9 M_{\odot}^1$. This is significantly higher than model calculations by e.g. Wellstein & Langer (1999) predict.

What can be said about the initial mass of 4U1700-37's progenitor? Given its origin in Sco OB1, the system should have the same age as the association. As discussed in Sect. 2.4, there likely is some spread in age within the association, but the observations indicate that at the moment of the supernova Sco OB1 was not older than 6 ± 2 Myr. The corresponding turn-off mass is $\geq 30^{+30}_{-10} M_{\odot}$ (Schaller et al. 1992). Following Iben & Tutukov (1985) (and case B mass transfer), the initial mass of a star that will explode as a $9 M_{\odot}$ star is $25 M_{\odot}$. Although Iben & Tutukov do not take into account the mass lost by the helium star, this result is consistent with our estimate of the progenitor mass based on the age of Sco OB1. If we take the

initial mass of the primary to be $30 M_{\odot}$, the initial mass of the secondary must have been less, and thus the present mass of HD 153919 cannot be higher than about $60 M_{\odot}$ (i.e. conservative mass transfer).

It is difficult to reconstruct the evolution of the massive binary before the supernova explosion. The main problem is the current short orbital period of the system. Applying Eqs. (4) and (5) in Nelemans et al. (1999), the orbital period before the supernova was a bit longer, about 4 days. In such a close binary it might well be that the primary starts transferring mass when it is still on the main sequence (case A mass transfer), but then one would predict a relatively large increase of the orbital period in case of conservative mass transfer (cf. Wellstein & Langer 1999). It might be that the evolution has been highly non-conservative due to strong stellar-wind mass loss and/or non-conservative Roche-lobe overflow. Case B mass transfer followed by a contact phase could produce systems like the Wolf-Rayet binary CQ Cep/HD 214419 (e.g. Marchenko et al. 1995) with an orbital period of 1.64 day. The latter system shows that in principle a short-period system like 4U1700-37's conjectured pre-supernova configuration can be produced (cf. Van den Heuvel 1973). A non-conservative evolutionary scenario for 4U1700-37 is also suggested by Wellstein & Langer (1999).

4. Discussion

We argue that the initial mass of the progenitor of 4U1700-37 was $\geq 30^{+30}_{-10} M_{\odot}$. This is relevant for the discussion which stars leave black holes and which stars end up as neutron stars. It is commonly believed that the most massive stars form black holes, while massive stars with a mass below a certain limit (M_{BH}) form neutron stars. This mass limit is under strong debate (e.g. Ergma & Van den Heuvel 1998). Maeder (1992) suggested that the observed helium and overall metal abundance is best reproduced if $M_{\text{BH}} \simeq 20 M_{\odot}$, while Timmes et al. (1996) set this limit at $\sim 30 M_{\odot}$. Whether the mass limit for black-hole formation in single stars can be compared to that in massive binaries is not clear (Brown et al. 1996). Kaper et al. (1995) set the lower limit for black-hole formation in a massive binary at $\sim 50 M_{\odot}$ based on observations of Wray 977 and X-ray pulsar companion GX301-2. But Wellstein & Langer (1999) propose that the initial mass of the neutron star in this system was much less, about $26 M_{\odot}$. The same authors derive for single stars that $M_{\text{BH}} \leq 25 M_{\odot}$.

However, for 4U1700-37 we now have an independent estimate of its progenitor mass, based on the age of its parent OB association. The only drawback is that it is not clear whether 4U1700-37 is a neutron star or a black hole. Up to now, X-ray pulsations, which would immediately identify the compact star as a neutron star, have not been detected. The presence of a cyclotron feature in the X-ray spectrum would also classify the X-ray source as a neutron star. Reynolds et al. (1999) modeled the X-ray spectrum of 4U1700-37, obtained with *BeppoSAX*, and report the presence of a possible cyclotron feature at an energy of

¹ In case of an asymmetric explosion, the derived mass would be smaller. However, the kick on the neutron star cannot be too large, because otherwise the system would have been disrupted.

~ 37 keV. If real, this observation yields a magnetic field strength of about $5 \cdot 10^{11}$ G, so that 4U1700-37 must be a neutron star. Without confirmation, the alternative that 4U1700-37 is a low-mass black hole cannot be excluded. If 4U1700-37 is a neutron star, a lower limit for black-hole formation in a massive binary derived from this system would be $M_{\text{BH}} = 30_{-10}^{+30} M_{\odot}$.

Acknowledgements. We thank the referee Dany Vanbeveren for carefully reading the manuscript. LK is supported by a fellowship of the Royal Netherlands Academy of Arts and Sciences. JD acknowledges NWO Spinoza grant 08-0 to E. P. J. Van den Heuvel. Ed Van den Heuvel and Gijs Nelemans are thanked for stimulating discussions.

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